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APPROXIMATE FORMULAS FOR THE COMPUTATION
OF CONNECTION DELAYS UNDER CAPACITY
RESTRICTIONS IN RAIL FREIGHT TRANSPORTATION

by

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ABSTRACT

The assignment of blocks of cars to train services at yards is an important step of the tactical planning of operations in rail freight transportation. This assignment depends upon the expected connection delays (the car waiting time until the designated train service is available), which are determined by the service frequencies, the train departure distribution and the service residual capacity. Bulk queues are a natural modelling tool for the connection delay. Historically, the service capacity has been considered an exogenous factor to the queueing formulations, which implied more cumbersome formulations for the tactical planning problem, as well as more perilous algorithms for solving them. Our approach is then to explicitly model both the connection delay and the capacity restrictions in the same bulk queueing formulation. Yet, very few algebraic results exist for these models and, even when exact numerical results may be obtained for some of them, the algorithms cannot be easily integrated into tactical planning network models which require easily computable closed form formulas to insure efficiency. It is thus of the outmost importance to derive approximate formulas for the average waiting times for these models. In this presentation, we describe the queueing formulation, the corresponding approximate formulas and some numerical results.

RÉSUMÉ

L'affectation, dans les gares de triage, des blocs de wagons aux services de train constitue une étape importante de la planification tactique du transport ferroviaire des marchandises. Les fréquences des services, la distribution des départs des trains, les capacités résiduelles des services sont les facteurs qui déterminent principalement cette affectation. Ces facteurs se trouvent réunis et sont estimés par le délai de connection : le temps qu'attendent les wagons classifiés jusqu'à ce que le service désigné soit disponible. Nous examinons une formulation du délai de connection comme le temps d'attente moyen dans un modèle de file d'attente en nombre ("bulk queue") intégrant explicitement la capacité des services. Nous proposons des formules (de forme analytiquement fermée) de calcul de ce temps d'attente qu'approximent la valeur exacte efficacement et avec une très grande précision. Nous présentons également quelques résultats expérimentaux.

I - INTRODUCTION

Terminals, the operations performed therein on both vehicles and freight and the resulting costs and delays, play a major role in freight transportation. Particularly so in rail transportation where cars going from different origins to various destinations are grouped into blocks which are then combined into trains, thus moving together from one terminal to another.

This car-block-train organization contributes greatly to the efficiency of the rail mode through the economies generated by the shared use of resources (motive power, fuel, manpower, etc.) during transportation. It is noteworthy that this advantage has been acknowledged even outside the rail industry. Thus, we assist presently at the adaptation of the rail organization to other freight transportation modes, e.g. the "road-trains" used in intercity trucking transportation.

Another direct consequence of the car-block-train organization is, however, a significant increase in the volume of terminal activities (mainly those activities related to individual cars : handling, sorting, storage, etc.) and the corresponding yard congestion, delays and costs. Thus, a typical car (and its load) spends most of its time in yards with only a relatively small part of its total travel time actually dedicated to movements between yards. This increased importance of terminal activities also significantly complicates the process of planning the operations of the whole rail system at both tactical/strategic and operational levels.

Consequently, understanding terminal operations and controlling yard delays may have a very significant impact on the system performance. Thus, a decrease in yard delays implies a decrease of the total transportation time which yields both an improvement in the quality of service

that the railroad offers to its clients, and a shorter car cycle time translating into a more efficient use of the company's resources. In addition, yard operations and delays play a major role in determining the transportation time reliability (2, 7, 20, 23, 24) and hence the quality of service and the railroad costs.

Yard delays may be controlled by locally analyzing and improving the operations of each individual yard. But, since decisions taken at one yard influence those of several other terminals and since yard policies interact with those concerning the other components of the rail system, yard delays may be more effectively controlled through an enhanced transportation plan built at the tactical planning level.

Tactical planning, as usually understood, aims at an efficient and rational allocation of existing resources to improve the performance of the whole system. Decisions made at this level are mainly concerned with the design of the service network (routes, modes and frequencies of the train services), the establishment of yard policies (car classification, train formation, etc.) and the routing of traffic through the service network. Since all these policies have network-wide impacts, strong economic and time-space interconnections and often conflicting objectives (low costs, high service quality), global, network-wide operating strategies are generated and combined into a comprehensive transportation plan.

Notwithstanding the choice of the level of control, be it the individual yard analysis or the tactical planning of operations, good yard and yard operations models are necessary to derive accurate estimations of such important performance characteristics as yard put-through cost, time and time variability.

Queueing formulations have generally and naturally been proposed as models for the various delays in freight terminals. Queueing models how-

ever, are for the most part quite analytically and computationally complex (13). Consequently, yard models either considered only simple queueing formulations, or used "queueing black boxes" to estimate delay characteristics.

Our study of yard operations is primarily motivated by the development requirements of a tactical planning model and has focused so far on the connection delays.

Connection, or the waiting of classified cars for their designated outbound train, not only is an important yard operation but, it also represents the link between yard and longhauling line operations. From a planning point of view, it therefore is the step where yard and traffic routing policies (train loads), service design policies (train frequencies) and train operational characteristics (train capacities) meet and have to be reconciled to achieve the system's objectives.

Our objective therefore is to propose a good connection delay model which integrates the important factor of the train service capacity and to derive accurate delay formulas that may be integrated into a global network optimization model.

The rest of the paper is organized as follows. Section II briefly describes the main yard operations and delays and reviews previous connection delay and network models. Section III presents our queueing model for the connection operation and the formulas used to estimate the resulting average connection delay. Section IV covers the integration of this model into a network model and examines the consequent variations in the performance of the network model. Section V concludes the paper.

II - LITERATURE REVIEW

While in a railyard, a car passes through five basic stages :

1. reception and inbound inspection;
2. classification;
3. connection;
4. train assembly;
5. outbound inspection and departure.

Descriptions of various yard designs, yard operations and their interrelations, may be found in Assad (1), Petersen (17, 18), and others. Here, we only want to sketch the general workings of the five basic stages. Note that we analyze yard operations from the point of view of the individual car as contrasted to the perspective of the whole train (as in Petersen (17) for example). We think, as do Turnquist and Daskin (25), that a "car" approach allows a greater accuracy and flexibility when modelling and analyzing yard operations and delays.

A railcar arrives at the receiving tracks of a yard either as part of an inbound train or as part of a block of cars left-off by a through train, or as a newly loaded (at the yard's loading facility or at the client's loading station) and delivered car. There, trains and, possibly, blocks are decomposed and each car is inspected.

Once inspected, cars are ready and queue for classification. During this stage, cars are sorted, according to their classification destinations (their final destination or the next classification yard on their transportation-plan-specified itinerary) into specified blocks and placed on classification tracks.

When classification is over, the blocks are ready either to be assembled into outbound trains, or to be added to a through train.

Assembly operations are performed by yard switch engines and their disponibility may generate queueing phenomena. In general however, delays at this stage are most commonly generated by the schedule of the departing trains (see the discussion in Turnquist and Daskin (25) and references 8, 20, 26, for example) which motivates the name, "connection", given to these delays. Engines are attached to the assembled blocks (when new trains are formed), cars are individually inspected and the train is ready for departure.

Of these stages, reception, departure and inspection are generally not considered as being bottleneck operations, while classification, assembly and connection traditionally are modelled using various queueing formulations.

A natural formulation for the connection delay is as the mean waiting time in a bulk-service queue (see Kleinrock (13) for a description of queueing theory terminology, scope and means) where a particular out-bound train service represents the service mechanism with an interservice time equal to the time between two successive departures (the service headway) and cars of the blocks assigned to that particular train service being the customers arriving to the queueing system.

Petersen (14, 16) proposes a (in Kendall's notation (12)) $M/E_k^{[\alpha]}/1$ bulk service queueing model, where cars arrive randomly according to a Poisson distribution, the interservice intervals are independently and identically distributed according to an Erlang distribution of order k and the batch size is constant and equal to the maximum train length α . The author also generalizes his results to the random batch size (model $M/E_k^{[Y]}/1$) and to the different block priorities cases (15). Petersen's work is among the most comprehensive on the subject. The solution of most of these models requires, however, the computation of the real root in the unit circle of a characteristic equation and is therefore difficult in all

but the simplest limiting cases (14). These models are part of a queueing structure used to compute yard throughput times for a rail network model (16).

Turnquist and Daskin (25) propose a Poisson arrival, infinite batch size bulk service queueing model for the connection delay included into their yard model. The relaxation of the train length restrictions yields a more analytically tractable model, which allows the authors to show that both the mean and the variance of the connection delay depend on the mean and variance of the service distribution, indicating that a more regular train departure schedule will reduce the average connection delay and its variance.

Powell (19) studies bulk queues and their applications to modelling delays in transportation terminals and proposes efficient numerical methods that may be used to compute the mean and variance of the waiting time in a queueing system of that type. These methods, based on iterative computation of the roots of the characteristic equation, represent an important development in the field of queueing studies, yet they cannot be used to derive analytic closed-form formulas for the mean connection delay.

Network models, when integrating connection delays, reflect this state of the art and use one of the following alternatives :

- i) the "black box" approach where an exogeneous yard model computes the values of the delays and passes them to the network model which defines the context parameters. A prime example of this approach is the Railcar Network Model (16). Note that the utilization of Powell's methods could greatly enhance this alternative;
- ii) the "simplified model" approach where train length restrictions are relaxed and a regular service hypothesis is used (e.g., 22, 25).

Crainic's tactical planning model for rail freight transportation (3, 4) uses this same approach, yet it also integrates into the objective function penalty terms to model the train capacity restrictions.

Recently, Gendreau (9, 10) proposed accurate closed form approximate formulas for the mean and variance of various bulk service queueing formulations used to model delays in a urban transit system. This approach showed very interesting perspectives and we decided to apply and develop it for the freight transportation systems.

This paper contains the results for the railyard connection delays of this effort.

III - A MODEL FOR RAILYARD CONNECTION DELAYS

A connection delay model should estimate the average waiting time of a car that has to go out of a particular yard on a specific train service. This estimate can then be used, jointly with estimates of costs and delays of other yard and longhauling operations, to determine, for tactical planning purposes, the routing of the traffic through the network.

To model the connection delay generated by each train service at every one of its stops, we use a particular class of queueing formulations, namely the bulk service scheduled departure queue models (9, 19).

The components of such a model are :

- a particular train service, originating or stopping at the yard, represents the service mechanism with one server;
- cars arriving through classification or transfer to be formed into the outbound train from the arrival process;
- the service headway corresponds to the interservice time interval;
- the available service capacity, equal to the difference between the service maximum capacity and the traffic load already on the service

(i.e. the traffic on the service before the yard and continuing after the stop at the yard), gives the batch size.

The mean waiting time in the queue of this queueing system represents then the sought for average connection delay generated by the train service at the specified yard.

For the arrival process, we suppose a Poisson distribution which is, in our opinion, the best approximation (especially at the aggregated, tactical planning level), both from a practical and theoretical point of view, of the actual process (11).

For the service mechanism, we assume a deterministic distribution to model the regular service (constant service headway) that is the current standard policy in most large railroads and the operating hypothesis of our tactical planning model. More general service distributions are possible and we present the corresponding results in Gendreau and Crainic (11).

The resulting scheduled departure bulk service with random batch size queue model, $M/D^{[Y]}/1$, belongs to the class of queueing formulations for which a closed-form formula for W_q , the mean waiting time in the queue, has not been found yet, nor is likely to be found in the foreseeable future.

Gendreau (9) examines, in an urban transit planning context, scheduled departure bulk service queues with fixed batch size and Erlang ($M/E_k^{[K]}/1$) or deterministic ($M/D^{[K]}/1$) service distributions, analyses their characteristics and deduces several approximations for their mean waiting times. He also shows that these "fixed batch size" approximations may also efficiently be used for the "variable batch size" models when the

Distribution of Y	$\bar{W}_q^S$			
	k=1	k=2	k=3	k=∞
Deterministic ($\bar{Y}=24$)	38.293	29.465	25.194	10.270
Binomial (0, 32) ($\bar{Y}=24$)	39.497	29.372	24.703	10.468
Binomial (0, 48) ($\bar{Y}=24$)	38.695	31.844	27.800	11.285
Binomial (0, 96) ($\bar{Y}=24$)	39.951	31.314	26.807	11.124
Mean	39.122	30.499	26.126	10.104
Maximum deviation	0.829 (2.1%)	1.345 (4.4%)	1.674 (6.4%)	0.515 (4.8%)
Simulation parameters	number of replications for each case = 10 warm-up time = 100 simulation time = 500 $\lambda = 1 \quad \frac{1}{\mu} = 19.2 \quad \rho = 0.8$			

Table 1 : The impact of the batch size variability on $\bar{W}_q^S$, the average simulated queue waiting time, in scheduled departure random batch size bulk service $M/E_k^{[Y]}$ /1 queues.

average batch size is not too small, as illustrated in Table 1. These approximations, giving closed-form formulas for the computing of the main queue characteristics, are generally very precise as shown in Gendreau (10) and Gendreau and Crainic (11), where the rail application is developed, and illustrated in Table 2.

Batch size K	Value	$\rho=0.80$	$\rho=0.90$	$\rho=0.92$	$\rho=0.94$	$\rho=0.96$	$\rho=0.98$
6	approx.	4.000	6.750	8.050	10.183	14.400	26.950
	exact	3.486	6.102	7.368	9.480	13.662	26.184
12	approx.	6.400	9.450	10.810	13.003	17.280	29.890
	exact	5.604	8.376	9.684	11.820	16.032	28.572
24	approx.	11.200	14.850	16.330	18.643	23.040	35.770
	exact	10.104	13.248	14.616	16.800	21.096	33.696
50	approx.	21.600	26.550	28.290	30.863	35.520	48.510
	exact	20.200	24.300	25.800	28.150	32.550	45.300
100	approx.	41.600	49.050	51.290	54.363	59.520	73.010
	exact	40.100	46.100	48.000	50.600	55.300	68.400
150	approx.	61.600	71.550	74.290	77.863	83.520	97.510
	exact	60.000	68.250	70.500	73.500	78.450	91.800
200	approx.	81.600	94.050	97.290	101.363	107.520	122.010
	exact	80.000	90.600	93.200	96.400	101.800	115.400

Table 2 : Exact (21) and approximate (hyperbolic) values for the mean queue waiting time in scheduled departure fixed batch size bulk service $M/D^{[K]}/1$ queues with unit arrival rate.

The best approximation for W_q , the mean waiting time in the queue of a scheduled departure fixed batch size bulk-service $M/D^{[K]}/1$ queueing model, is the "hyperbolic" formula (9) :

$$\tilde{W}_q^h = \frac{1}{2\mu} \left(1 + \frac{\rho}{K(1-\rho)} \right)$$

where $\tilde{W}_q^h$: hyperbolic approximation of W_q ;

λ : arrival rate;

$\frac{1}{\mu}$: average interservice time arrival;

K : batch size;

ρ : utilization coefficient

$$\rho = \frac{\lambda}{K\mu}$$

Note that for the model with variable batch size, one simply replace the fixed batch size K with $E[Y]$, the average batch size.

We have extensively tested the accurateness of the approximation by comparing its results to the exact value of the mean waiting time for an extended range of batch sizes and service intervals. Table 2 displays a characteristic sample of the results indicating that the approximation is very accurate over the whole range of test problems. And, since it represents an analytic closed-form formula for the average connection delay, the approximation is also suitable for inclusion into more general terminal and network models.

IV - HOW IT PERFORMS

For the purpose of evaluating more realistically the performances and benefits of our method of modelling and computing connection delays, we introduce the approximation formula into a tactical planning model for rail freight transportation.

Structurally, the model is formulated as a multimode service network design problem with a multicommodity flow distribution subproblem and an objective minimizing a generalized system cost which includes operating and delay costs (3, 4).

The model is based on two central elements : the service network which specifies the set of feasible routes on which train services may be operated, and the itineraries defining how the traffic moves on the network. A train service is characterized by its route (origin, destination, intermediate stops and physical path in the network) and mode (or train-type, defined by its speed-priority). The frequency of the service is defined as the number of trains operated on its route during the planning period and is determined by the model. An itinerary specifies a feasible journey for the traffic of a given traffic-class (an origin-destination

type of commodity combination with positive transportation demand) : the service path followed in the service network and the sequence of (re)classification yards along this path. The distribution of the traffic of each traffic-class among its itineraries is also determined by the model.

It is at the level of the objective function that, while looking for the best service at minimum cost, trade-offs are considered between the minimization of operating costs and the minimization of the delays imposed on trains and traffic by congestion and operating policies in yards and on the road. Operating costs represent the real cost of handling and moving freight, cars and trains. As for delays (for classification, connection, longhauling, etc.), they are converted into costs via unitary delay costs defined for each service and traffic-class.

The model states that the total system cost has to be minimized while satisfying the demand for transportation and the usual nonnegativity and integrality (for frequencies) constraints.

The formulation yields a non-linear, mixed-integer, multimode, multicommodity flow problem with a particular structure : explicit constraints bind only the continuous variables, the resulting constraint-matrix displaying a block-diagonal form with each block being a one-row matrix corresponding to the flow conservation equation of a given traffic-class. This structure allows the formulation of an efficient algorithm (5), based on a decomposition scheme, which works alternatively on the following subproblems :

1. Service network design : given a fixed traffic distribution, modify the frequencies to improve the objective. If this is not possible, stop. A method of finite differences is used to determine the frequencies which will be modified.
2. Traffic routing and distribution : for a given level of service, determine the optimal traffic distribution. The problem is solved by a

decomposition procedure which cyclically considers each traffic-class, while all others are kept fixed. For each subproblem, a new itinerary is first generated by shortest-path-like techniques, using marginal costs as unit costs, on the service network. The traffic distribution is then reoptimized.

This methodology is successfully applied to the rail case (6) and to the "less-than-truckload" trucking freight transportation (21) case.

In this formulation, yard connection is modelled as an infinite batch size bulk service queue with Poisson arrivals and deterministic (regular) service. This gives an average connection delay of $\frac{L}{2t_\ell}$ for the traffic going out of yard j on a service ℓ with frequency t_ℓ over a planning period of length L . The service capacity restrictions are considered in a delay-penalty term (with c_ℓ^p the overcapacity penalty cost for service ℓ)

$$c_\ell^p [\text{minimum} \{ 0, \alpha t_\ell - x_{p_{j*}}^\ell \}]^2$$

which compares the maximum service capacity with the actual load $x_{p_{j*}}^\ell$ on the service leg p_{j*} from the yard j to the next stop on service ℓ 's route.

This modelling approach, while giving very satisfactory results, is rather inelegant, presents some analytical complexities and increases the required computational effort. The use of the scheduled departure queue formulation and of the approximation formulas alleviates some of these problems.

Define

- $\tilde{x}_j^\ell$: total number of cars that take service ℓ out of yard j ;
- $\bar{x}_j^\ell$: volume of traffic already on service ℓ (i.e., travelling on service ℓ both before and after the stop at yard j);

$$\bar{x}_j^\ell = x_{p_{j*}}^\ell - \tilde{x}_j^\ell$$

βt_λ : service capacity, with $\beta > \alpha$;

x_j^λ : residual capacity of service λ at yard j ;

$$\begin{aligned} x_j^\lambda &= \beta t_\lambda - \bar{x}_j^\lambda \\ &= \beta t_\lambda - x_{p_{j*}}^\lambda + \tilde{x}_j^\lambda \end{aligned}$$

λ_j^λ : arrival rate

$$\lambda_j^\lambda = \frac{\tilde{x}_j^\lambda}{L}$$

$\frac{1}{\mu_j^\lambda}$: headway of service λ at yard j

$$\frac{1}{\mu_j^\lambda} = \frac{L}{t_\lambda}$$

K_j^λ : batch size

$$K_j^\lambda = \frac{x_j^\lambda}{t_\lambda} = \beta - \frac{\bar{x}_j^\lambda}{t_\lambda}$$

ρ_j^λ : utilization factor

$$\rho_j^\lambda = \frac{\tilde{x}_j^\lambda}{\beta t_\lambda - \bar{x}_j^\lambda}$$

Then γ_j^λ , the average connection delay for service λ at yard j , is given by :

$$\begin{aligned} \gamma_j^\lambda &= \tilde{w}_q^h \\ &= \frac{L}{2t_\lambda} \left\{ 1 + \frac{\tilde{x}_j^\lambda t_\lambda}{(\beta t_\lambda - \bar{x}_j^\lambda)(\beta t_\lambda - \bar{x}_j^\lambda - \tilde{x}_j^\lambda)} \right\} \\ &= \frac{L}{2t_\lambda} \left\{ 1 + \frac{\tilde{x}_j^\lambda t_\lambda}{(\beta t_\lambda - x_{p_{j*}}^\lambda + \tilde{x}_j^\lambda)(\beta t_\lambda - x_{p_{j*}}^\lambda)} \right\} \end{aligned}$$

Note that, as γ_j^l is a congestion function, the average connection delay goes to infinity as the service load $X_{p_j^*}^l$ grows toward the service capacity (i.e., as the "new" traffic $\tilde{X}_j^l$ grows toward the batch size) as illustrated in figures 1, 2 and 3. As trains may, however, be run at full capacity, one needs to use in the queueing model a modified capacity figure, β , slightly larger than the original one. Figures 1, 2 and 3 display graphs of the average connection delay (normalized for unit service rate) versus the service load for five values of β ($110 = \alpha$, 111, 112, 115, 120), for three cases : service completely empty on arrival at the specified yard (fig. 1), service 45% full (fig. 2) and service 73% full (fig. 3). Examining these graphs, we observe that a small increase (not more than 10%) of the value of α is sufficient to insure the proper consideration of the capacity restrictions.

Experiments with the modified tactical model involve the same problems solved with the initial version of the model (5, 6). We use $\beta=1.1\alpha$.

Data, kindly supplied by the Canadian National Railways (C.N. Rail), encompasses a physical network representing the tactically aggregated western part of C.N. Rail's network, several traffic forecasts and the corresponding service networks generated using CANAT, C.N. Rail's macro tool for medium-to-long term planning (27). It also includes our own generated initial service networks for the same traffic data. The different types of experiments, the quality of the results and the performance of the algorithms are presented and discussed in some detail in Crainic and Rousseau (5) and Crainic (6).

Preliminary results with the modified version of the model are very encouraging.

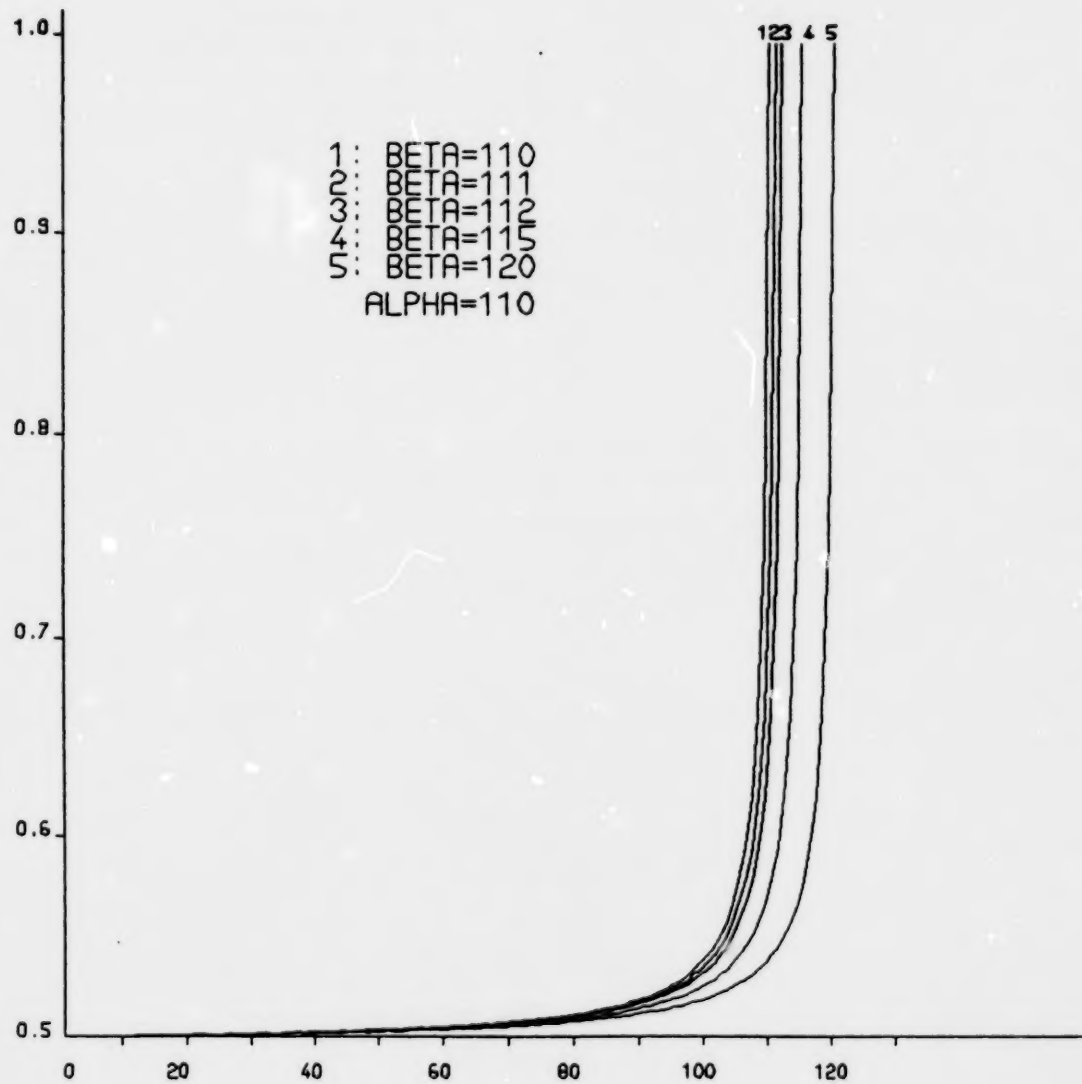


Figure 1 : Normalized average connection delays vs. service load for an initial load of 0 railcars.

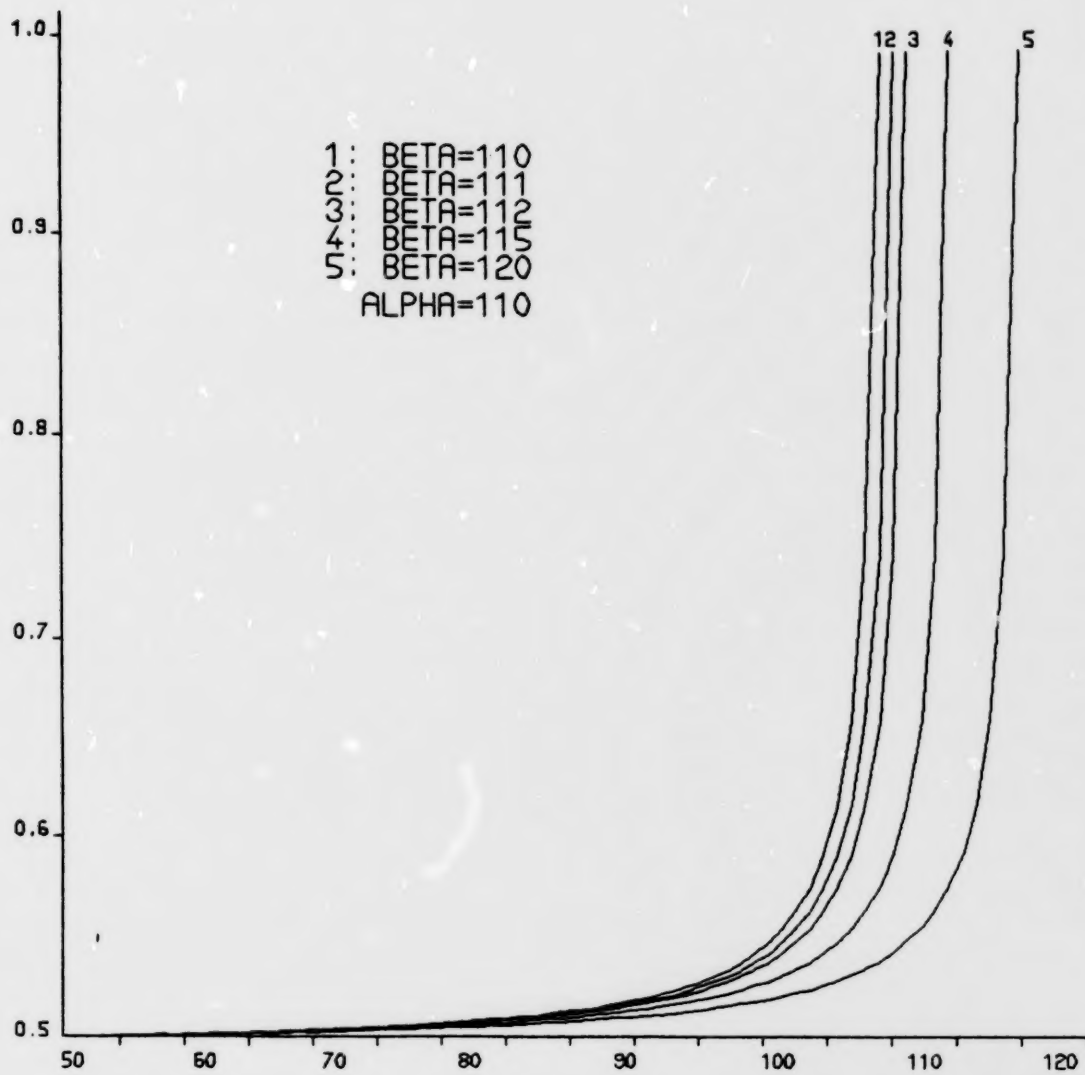


Figure 2 : Normalized average connection delays vs. service load for an initial load of 50 railcars.

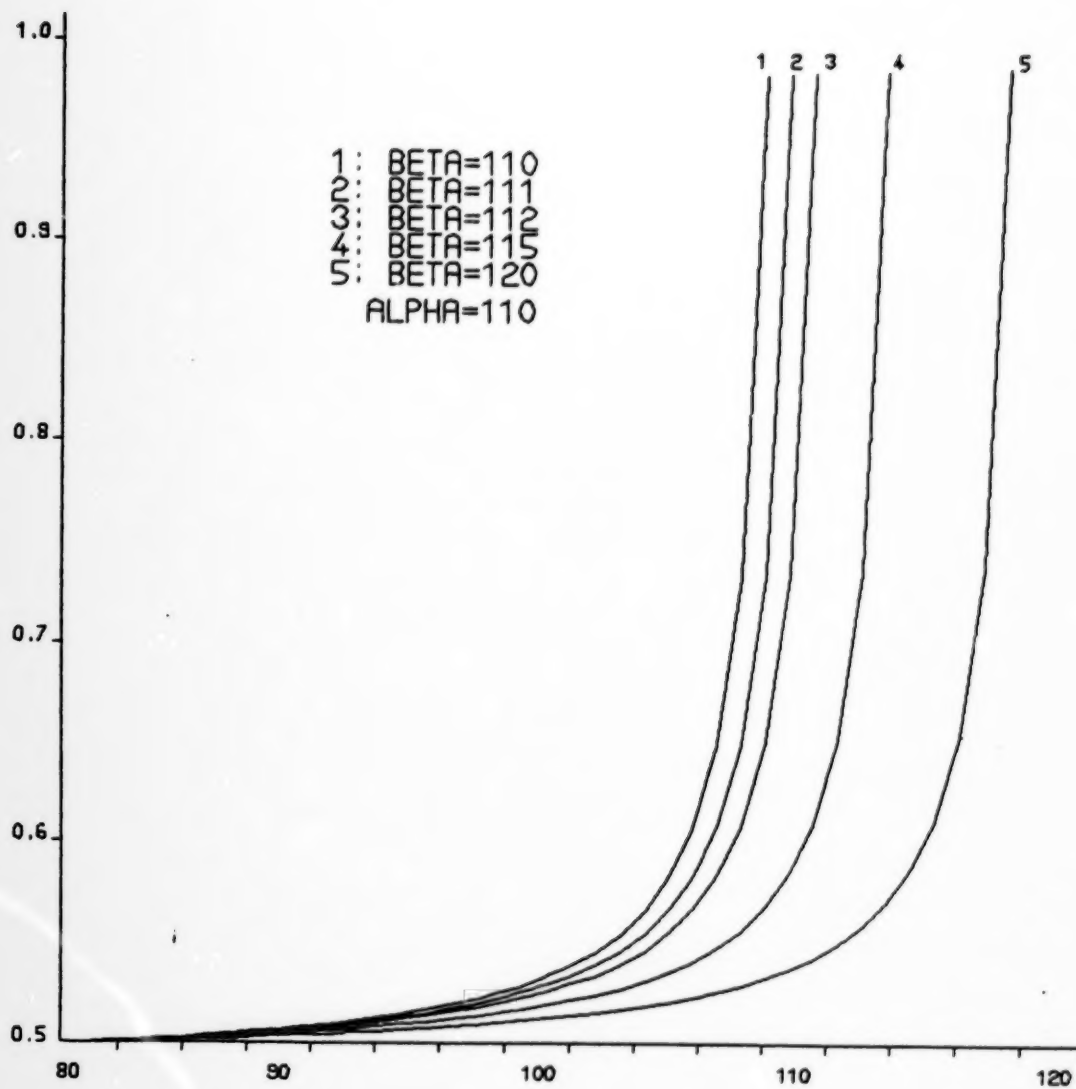


Figure 3 : Normalized average connection delays vs. service load for an initial load of 80 railcars.

As expected (the problem features a great number of quasi-optimal solutions with virtually the same value for the objective function) we obtain physically different solutions than previously. The quality of the solutions, however, are of the same high level, for all criteria used (5, 6). Resolution times are also of the same order of magnitude as previously (5). If the frequency modification procedure is more efficient, slightly more time is needed to reoptimize the traffic distribution. This is mostly due to the fact that queueing formulations need very fine tunings in order to yield optimal results. Thus, we presently use the same class of scheduled departure fixed batch size bulk service queue models for all yard-train service occurrences when, in fact, random batch size bulk service queue models with heterogeneous servers and selective customers (9, 10, 11) are better suited to modelize services linking large yards via heavily used corridors. Tests using these formulations are the main subject of our next experiments.

CONCLUSION

We presented a method which permits both the formulation of a precise model for railyard connection delays and the derivation of closed-form formulas for the average connection delay. These formulas are obtained through accurate approximations of the waiting time in the queue of a scheduled departure fixed batch size bulk service queueing model. Their utilization allows the formulation of more elegant and computational efficient global tactical strategic planning models for rail freight transportation.

We plan to generalize these results to other intercity freight transportation modes and to apply the same methodology to the other terminal delays, especially the classification delays.

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